National Aeronautics and Space Administration

Heavy Lift Launch Vehicle Study

May 20, 2010

Study Objectives and Guidelines

HLLV Data team was charted by senior agency leadership in the Fall of 2009 to:

Study HLLV alternatives and provide NASA leaders performance, cost, schedule, safety/reliability, mission capture, and operability data to support informed, objective launch architecture decision.

- **Major Guidelines included:**
  - The ultimate destination for purposes of the exercise is Mars – mission should lead towards developing Mars capability
  - Requirements generated from a mission sequence (roadmap) within a *Modified* Flex Path Scenario
  - Develop IOC schedule / compelling mission capability options
  - Crew capable – ISS not precluded
  - Work within budget scenarios
  - Defer technology plan, but considers impacts of “game changing” technologies
  - Propellant transfer/depot capability not available for early missions
  - Consider cooperation between robotic and human
  - Consider and understand the available civil service workforce and facilities
  - Consider options for international partnerships
  - Orion is the crew vehicle
  - Assess Orion impacts parametrically (Defer detailed Orion impact assessment)
  - The architecture for purposes of the exercise should drive toward a heavy lift capability as soon as possible by minimizing cost (near term and LCC) and schedule.
  - Cost based on current business model
  - Cost analysis performed as stand-alone – no credit taken for continuation of Shuttle or Ares I

HLLV Study Timeline

- Study Team Formed in September 2009
  - Cross Agency Human Spaceflight Team
  - Subteams for Mission Architecture, HLLV Architecture, Systems Development, HLLV Data, Cost, Safety and Reliability and Ground Ops
  - Briefed Results to Senior Board (NASA HSF and Center Leadership) end of 2009
  - Performed Updated Study Spring of 2010
    - Action to Review RS-68 and RS-25 engine costs
    - Added additional RP based and RS-68 configurations
  - Briefed Updated Results in April 2010 to Senior Review Board
    - No further actions
  - Study Closed out in April 2010

Missions Assessed

- Lunar Flyby – free-return “figure eight” (Single Launch)
- Earth-Moon L1 (Single Launch)
- Lunar Orbit – high and low orbits assessed (Single Launch)
- Lunar Surface (Dual Launch, Cx and Apollo class)
  - Required mass will depend upon ultimate mission requirements
  - Two “bookend” missions were developed to span this requirements space
- Earth-Sun L2
  - Long-duration Orion test flight
- NEOs (Dual Launch)
  - Several representative lower-energy targets assessed
  - No large effort to optimize mission or vehicles at this point, basic understanding of performance sought
- High Mars Orbit – crewed segment of Mars DRA 5.0 utilized
- Mars – modified DRA 5.0

HLLV Propulsion Tradespace

Core Stage Engine

SSME (RS-25D) (LOX/LH_2)
(HLLV GR&A, 11/15/09)

- Inventory allows for 3 flights with existing Shuttle MPS
- Vacuum Thrust = ~491 klb_m @ 104.5%
- I_{sp} = ~450 sec

RS-25E (LOX/LH_2)
(HLLV Engine Team Data, 11/17/09)

- Expendable
- Vacuum Thrust = ~512 klb_m @109%
- Isp = ~450 sec
- NASA is only purchaser

RS-68B (LOX/LH_2)
(HLLV Engine Team Data, 11/17/09)

- Upgraded Delta IV RS-68
- Current RS-68A upgrade program ongoing
- Vacuum Thrust = ~797 klb_m @ 108%
- I_{sp} = ~409 sec
- NASA is secondary purchaser (Air Force)
- Requires human rating, operability improvements

New US LOX/RP Staged Combustion Cycle
(PDR Package; prototype)

- Clean Sheet Design (PDR, TRL 5)
- Vacuum Thrust = ~1,130 klb_m @ FPL
- I_{sp} = ~324 sec

Core Stage Diameter is a fallout of the Core Stage Engine Selected. RP Core stage engine trades with solids.

Upper Stage Engine

J-2X (CDR package)

- Derived from Saturn V J-2
- Post-CDR
- Designed for human-rated use on Ares I
- Vacuum Thrust = ~294 klb_m @ 100%
- I_{sp} = ~448 sec
- Requires 1 per launch on LOX/LH_2 CS, and 4-5 on LOX/RP CS

RL10A4-3
(HLLV Engine Team Data, 11/17/09)

- Derived from current RL10A4-2 and RL10B-2
- Max Vacuum Thrust = ~24 klb_m @ FPL
- Vacuum Thrust = ~21 klb_m @ derated power level
- I_{sp} = ~452 sec
- Requires ~4 per launch

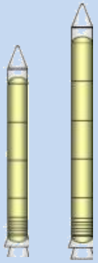
First Stage Booster

PBAN – 4 segment (074-99)

- Current Shuttle RSRB
- Thrust = ~3.1 Mlb_m @ T+1sec
- Burn time = ~126 seconds

PBAN – 5 segment (069-07)

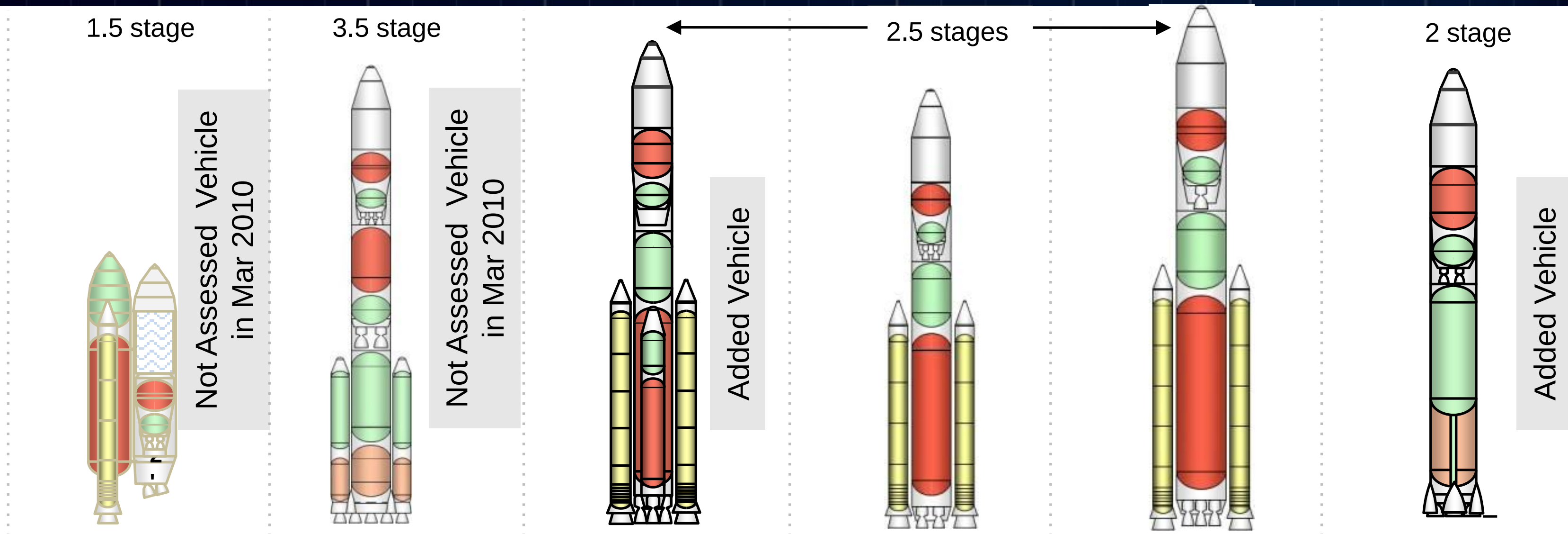
- Current Ares I RSRB
- First development motor fired successfully, 2nd dev. In work, opportunity to optimize for vehicle options
- Thrust = ~3.5 Mlb_m @ T+1sec, Burn time = ~126 seconds



HTPB – 5 segment (309-07)

- Composite Case / Higher Pressure
- Thrust = ~4.7 Mlb_m@ T+1sec
- Burn time = ~ 108 seconds

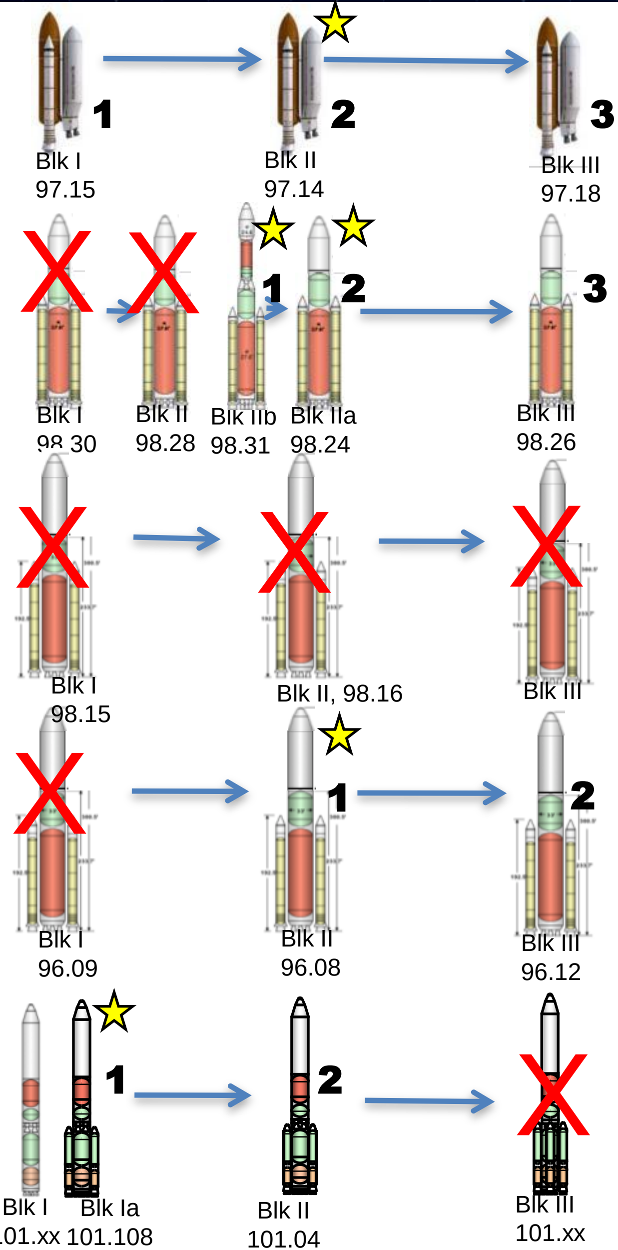
HLLV Trades
Reference Configuration Baselines (Nov. '09 – Mar. '10)



Key Trade	Shuttle Sidemount	27.5' RP	27.5' Inline	27.5' Inline	33' Inline	33' RP
Geometry	Basic Shuttle Geometry; Carrier Development Required	Shuttle ET diameter	Shuttle ET diameter	Shuttle ET diameter	Saturn V heritage 33' diameter	Saturn V heritage 33' diameter
Booster	4 segment Shuttle PBAN booster; Evolvable to 5 segment PBAN	Atlas V CCB w/ RD-180, evolved to New RP	5 segment Shuttle PBAN booster/Liquid Rocket Booster (2 RS68B), evolvable to HTPB	5 segment PBAN booster, evolvable to HTPB	5 segment PBAN booster, evolvable to HTPB	N/A
Core Stage Engine	SSME (RS-25D) until inventory depleted, RS-25E afterwards	RD-180, evolved to New RP	3 RS-68B evolvable to RS-68B E/O (regeneratively cooled, larger expansion ratio) option	5 RS-25E	RS-68B evolvable to RS-68B E/O (regeneratively cooled, larger expansion ratio) option	6 1.7 m lbf thrust class LOX/RP-1 engine evolvable to 2 m lbf thrust
Upper Stage Engine	RL10A4-3 or J-2X	J-2X for 2nd stage, RL10A4-3 for 3rd stage	1 J-2X	4 RL10A-4-3	J-2X	2 J-2X-285 or 1 RS-68B E/O (regeneratively cooled, larger expansion ratio)

HLLV Study Trade Tree (Nov 2009)

☆ System Owner Best Estimate
X Eliminated



Sidemount

Blk I – 4 seg RSRB's , std ET, Fly out existing assets (MPS, Avionics, SSME)
Blk II – 4 seg RSRB's, minor ET mods, (MPS for 109% PL, avionics, RS-25E @ 109% PL)
Blk III – 5 seg SRB's, minor ET mods, RS-25E @ 111% PL, MPS for 111% PL

27.5' Inline SSME Based

Blk I – 4 seg RSRB's , Fly out existing assets (4 SSME per vehicle @ 104.5% PL)
Blk II – 4 seg RSRB's, 4 RS-25E @ 109% PL
Blk IIb – 5 seg Optimized SRB's, 5 RS-25E @ 109% PL with Ares I Upper Stage
Blk IIa – 5 seg Optimized SRB's, 5 RS-25E @ 109% PL)
Blk III –5 seg HTPB SRB's, 5 RS-25E @ 115% PL, Composite Shroud

27.5' Inline RS-68 Based

Blk I – 4 seg RSRB's , 3 RS-68A
Blk II – 5 seg RSRB's, 3 or 4 RS-68B
Blk III – Upgraded 5 seg SRB's, , 3 or 4 RS-68E/O

33' Inline RS-68 Based

Blk I – 4 seg RSRB's w/ spacer , 5 RS-68B
Blk II – 5 seg Optimized RSRB's, 5 RS-68B
Blk III – 5 seg HTPB SRB's, , 5 RS-68E/O, Composite Shroud

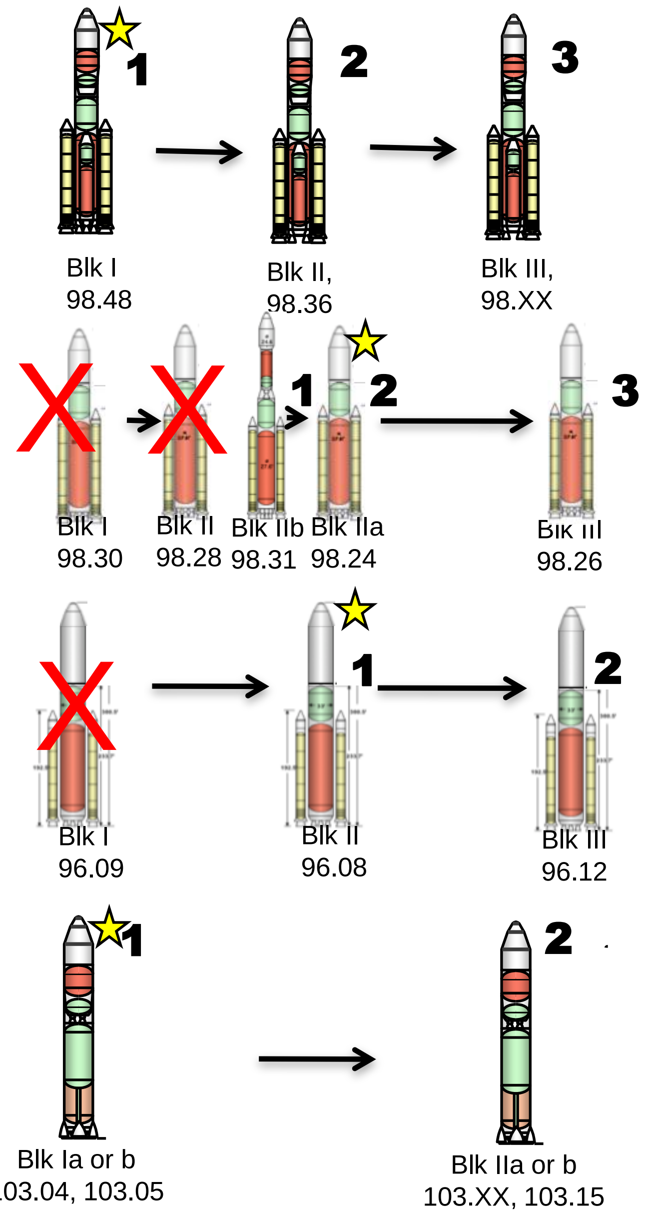
RP-1 Based 27.5' Core

Blk I – 27.5' Core using 5 RD-180
Blk Ia – Blk I w/ 2 Atlas V Boosters and 5 RD-180 on Core and 1 ea per Booster
Blk II – Blk Ia w/ New United States Engines
Blk III – Blk IIA with 2 additional boosters and Composite, RP-1 Tank and Shroud

HLLV Study Trade Tree (Jan 2010)

System Owner Best Estimate

X Eliminated



27.5' Inline LRBSRB RS-68 Based

Blk I – 5 Seg. PBAN, 2 LRB, 3 RS-68-B Core & J-2X EDS
Blk II – 5 Seg. PBAN, 2 LRB, 3 RS-68-E/O Core & J-2X EDS
Blk III – 5 Seg. HTPB SRB's, 2 LRB, 3 RS-68-E/O Core & J-2X EDS

27.5' Inline SSME Based

Blk I – 4 seg RSRB's , Fly out existing assets (4 SSME per vehicle @ 104.5% PL)
Blk II – 4 seg RSRB's, 4 RS-25E @ 109% PL
Blk IIb – 5 seg Optimized SRB's, 5 RS-25E @ 109% PL with Ares I Upper Stage
Blk IIa – 5 seg Optimized SRB's, 5 RS-25E @ 109% PL)
Blk III –5 seg HTPB SRB's, 5 RS-25E @ 115% PL, Composite Shroud

33' Inline RS-68 Based

Blk I – 4 seg RSRB's w/ spacer , 5 RS-68B
Blk II – 5 seg Optimized RSRB's, 5 RS-68B
Blk III – 5 seg HTPB SRB's, , 5 RS-68E/O, Composite Shroud

RP-1 Based 33' Core

Blk Ia – 6 1.7 m lbf RP-1 booster engines, 2 J-2X-285 US engines
Blk Ib – 6 1.7 m lbf RP-1 booster engines, 1 RS-68B E/O US engine
Blk IIa – 6 upgraded 2 m lbf booster engines, 2 J-2X-285 US engines
Blk IIb – 6 upgraded 2 m lbf booster engines, 1 RS-68B E/O US engine
NOTE: a vs. b dependent upon performance vs. reliability and cost selection criteria

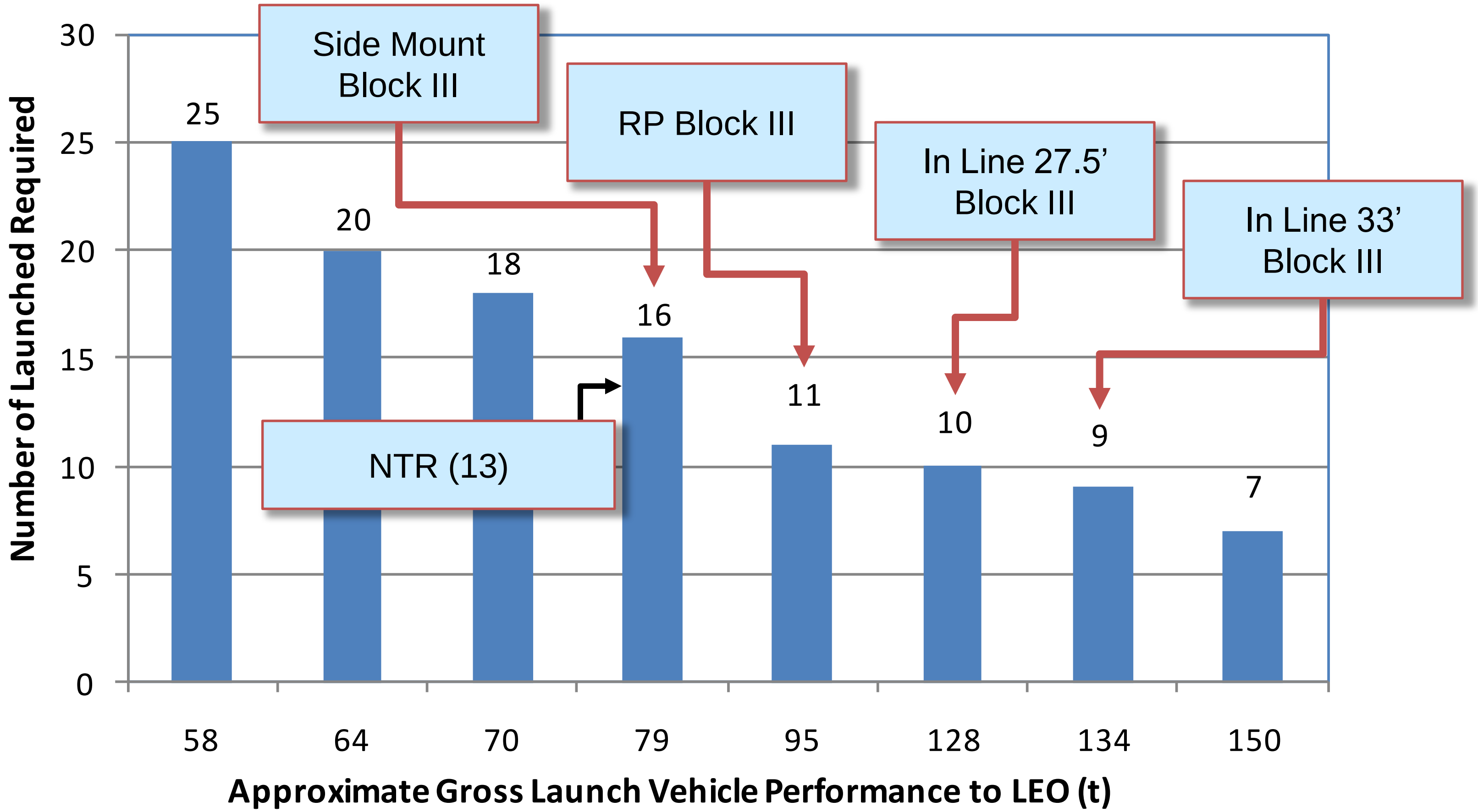
Mission Capture – Evolved Capability Vehicles

Mission/Concept	Sidemount Blk III RS-25	Inline (27.5) Blk II RD-180	Inline (27.5') LRB/SRB (HTPB) 5xRS-68E/O, 1xJ-2X (estimated)	Inline (27.5') Blk IIA 5xRS-25, SRB (HTPB) 4xRL-10	Inline (33') Blk II 5xRS-6E/O, SRB (HTPB) , 1xJ-2X	Inline (33) RP 6xF1 class (2M), 2xJ-2X (estimated)
Lunar Fly-By	G	G	G	G	G	G
Earth-Moon L1	G	G	G	G	G	G
Lunar Orbit - Easy	G	G	G	G	G	G
Lunar Surface – Apollo (2x)	Y/G*	G	G	G	G	G
Lunar Orbit - Hard	Y	G	G	G	G	G
Sun-Earth L2	R	G	G	G	G	G
Lunar Surface – Cx+ (2x)	R	G	G	G	G	G
NEO GP2 (2x)	R	R	Y	Y	Y	Y
NEO OJ142 (2x)	R	R	R	R	R	R
NEO AO10 (2x)	R	R	R	R	R	R
NEO SM84 (2x)	R	R	R	R	R	R
Mars DRA 5.0	**16**	**11**	**9 (est.)**	**10**	**9**	**7 (est.)**
Mars Orbital	**7**	**5**	**3 (est.)**	**4**	**3**	**3 (est.)**

*LOX/Methane Lander/CEV Req'd

G: HLLV Net Capability > Mission Req.
Y: HLLV Gross Capability > Mission Req. > HLLV Net Capability
R: Mission Req. > HLLV Gross Capability

Example Mars Mission Manifest Sensitivity to Launch Vehicle Capability – Chemical Aerocapture Architecture



Notes:

- Mission strategy consistent with Mars Design Reference Architecture 5.0 (NASA-SP-2009-566)
- Reduced Design Reference Architecture content (4 crew)
- No dedicated crew launch (assumes crew can launch with a cargo element)
- Numerous advanced technologies incorporated
- 70 t wet lander assumed for all cases
- Low-Earth Orbit defined as 407 km circular for these cases

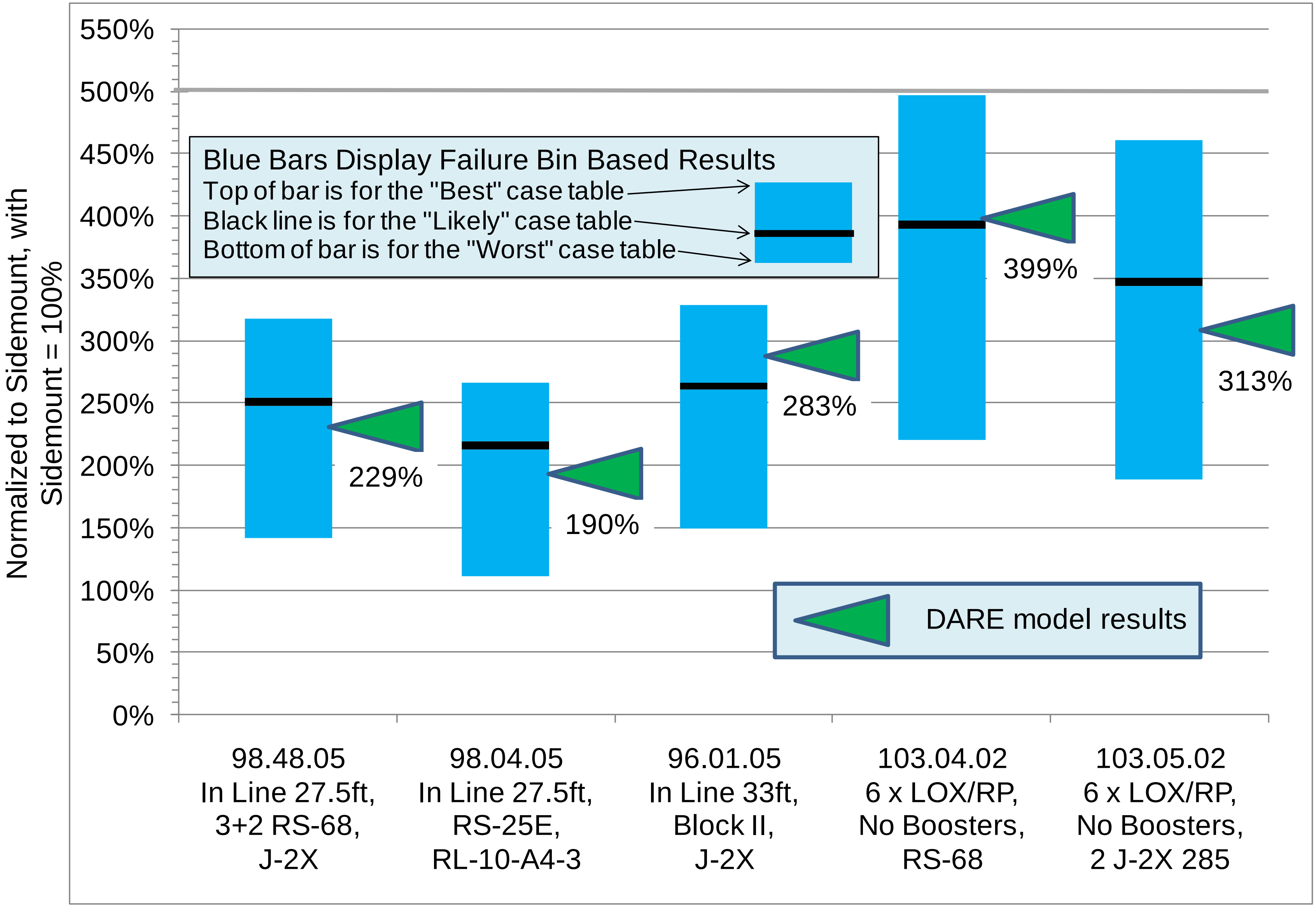
Data Summary of All Vehicles

* All Costs generated in this study are normalized to sidemount, with sidemount being = 1

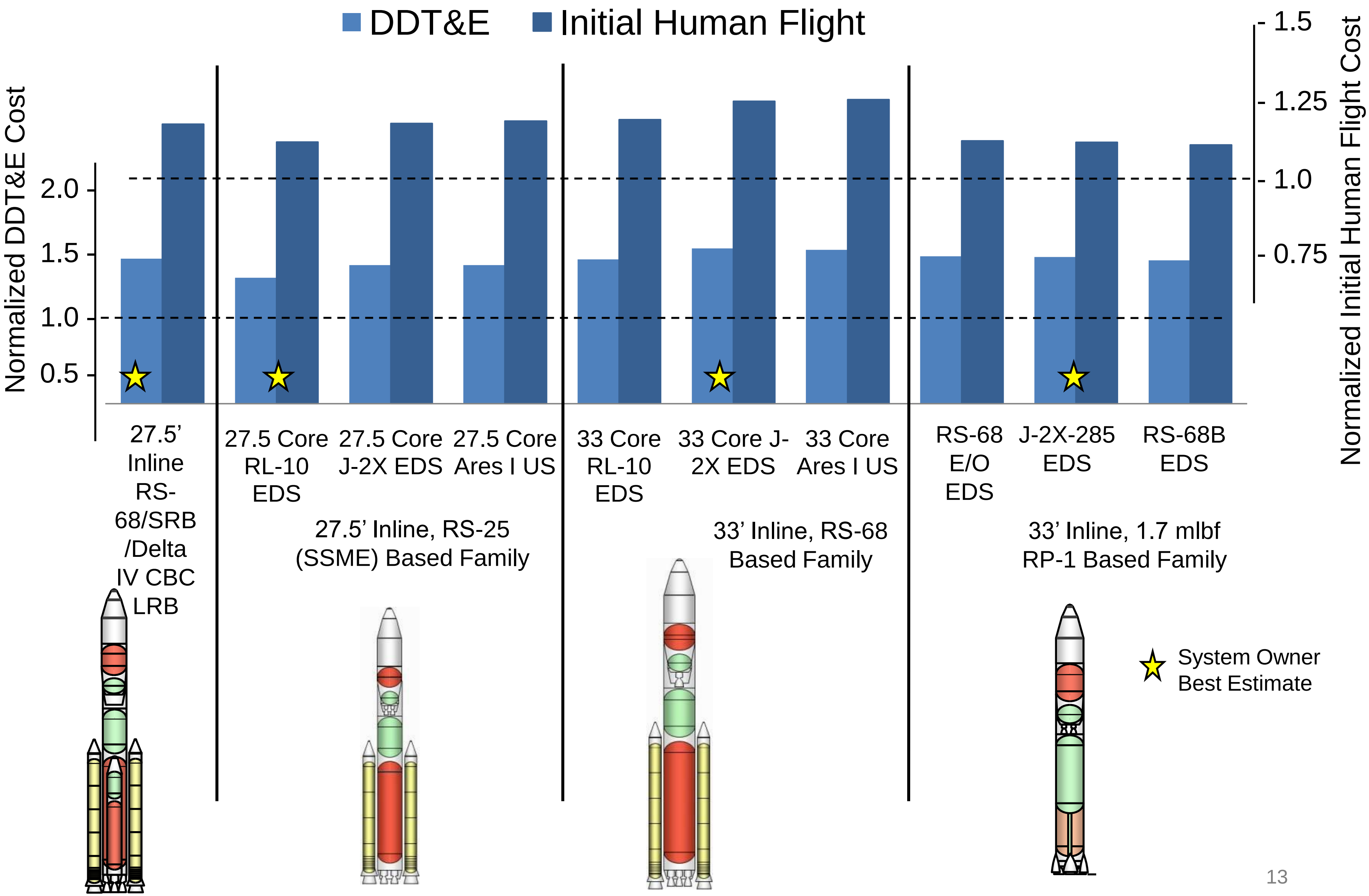
Concept	Sidemount RS-25E 4xRL-10 2x4Seg SRB 97.14.00	Inline (27.5) 3xRS-68 B 2xRS68B LRB 1xJ2X 2x5Seg SRB	Inline (27.5) 5xRS-25E 4xRL-10 2x5Seg SRB	Inline (33) 5xRS-68B 1xJ-2X 2x5Seg SRB	Inline (27.5) RP 7xRD-180 4xJ-2 5xRL-10	Inline (33) RP 6x1.7 m lbf thrust 2xJ-2X-285	Cx Architecture EOR 1.5 Launch
Mission Capture	Lunar Apollo (-)	Lunar Cx (+)	Lunar Cx (+)	Lunar Cx	Lunar Cx	Lunar Cx	Lunar Cx
Performance (IMLEO) (Estimated Gross, t)	80.2	131.7	118.4	127.9	99.7	149.4	~23 / ~161 Ares I / Ares V
Performance (TLI) (Gross, t)	31.2	51.3	49.2	46.2	39.9	45.1	~59 / ~70 Ares V/Ares I+V
Extensibility (Mars DRA 5.0 # flights, Evolved Vehicle)	16	9	10	9	11	7	1 / 8 Ares I / Ares V
Safety (LOC/LOM) (Normalized with sidemount = 1)	1.0 / 1.0	0.4 / 0.8	0.7 / 1.4	0.4 / .8	0.6 / 1.5	0.3 / 0.6	Ares I: 0.1 / 0.2 Ares V: N/A / 0.9
Schedule to IHF	2018 (16)	2019 (18)	2018	2019	2019	2019	2015 / 2020
Schedule to First Flight	2017 (15)	2018 (17)	2017	2018	2018	2018	2014 / 2019 Ares I / Ares V
Cost (DDT&E)	1.0	1.5	1.3	1.7	1.4	1.6	1.8
Cost to IHF	1.0	1.2	1.1	1.2	1.1	1.0	0.7/ 1.4 Ares I / Ares I+V
$/lb to LEO	1.0	0.7	0.7	0.6	0.9	0.5	0.7
$/lb to TLI	1.0	0.7	0.7	0.7	0.9	0.7	0.7
Annual recurring (4 flights per year)	1.0	1.0	1.1	1.0	1.1	1.0	1.0

Note: A straight comparison to the program is not 100% feasible due to different Mission Architecture configurations, fidelity and maturity of data, and groundrules and assumptions made for the HLLV study. The data shown is the best interpretation mapping the Program and the Study team could make in the time available.

Loss of Crew During Ascent (assuming crew launched on HLLV) (2 Methodologies)

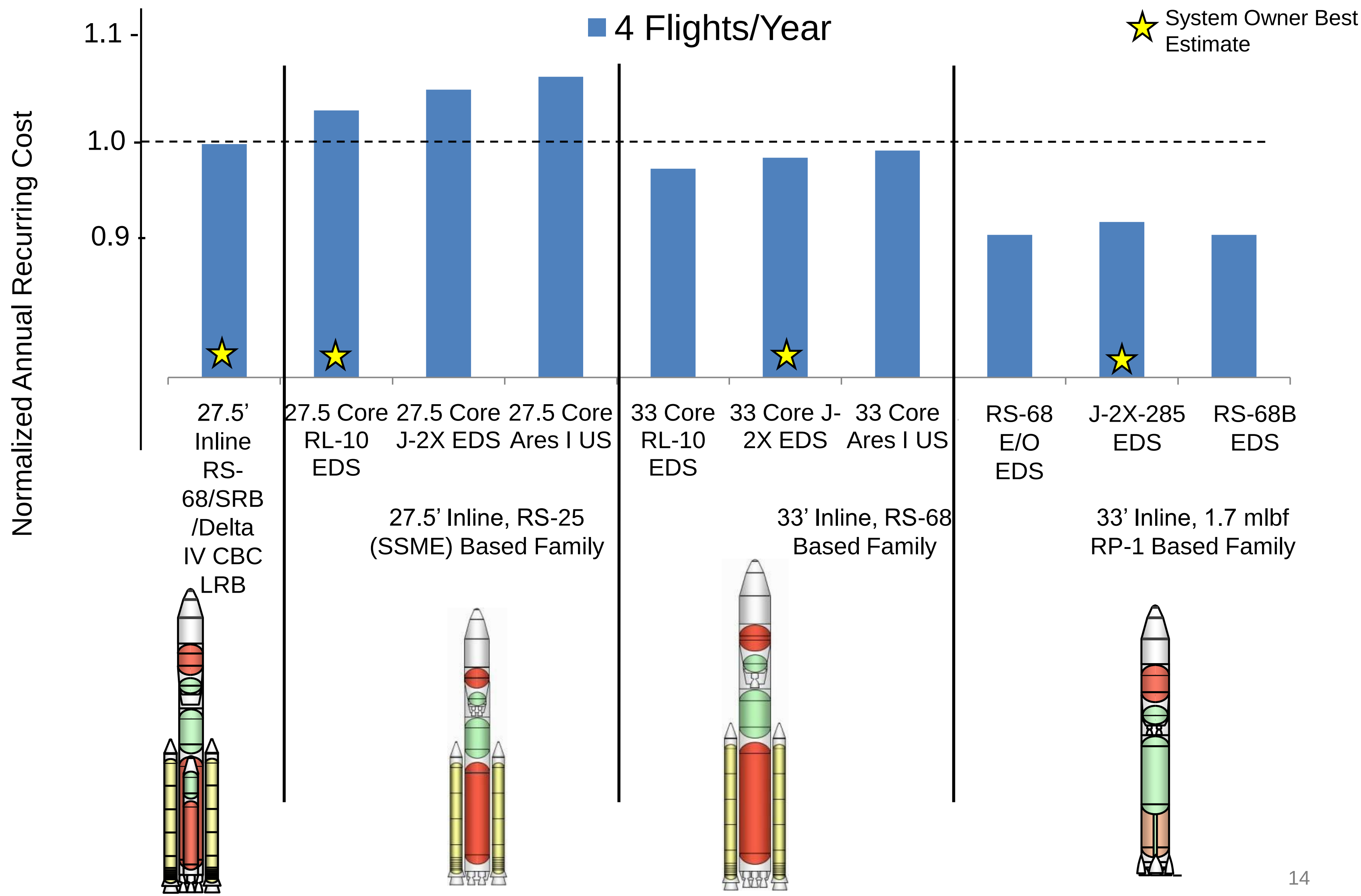


Development Cost



* All Costs are normalized to sidemount, with sidemount being = 1

Annual Recurring Cost



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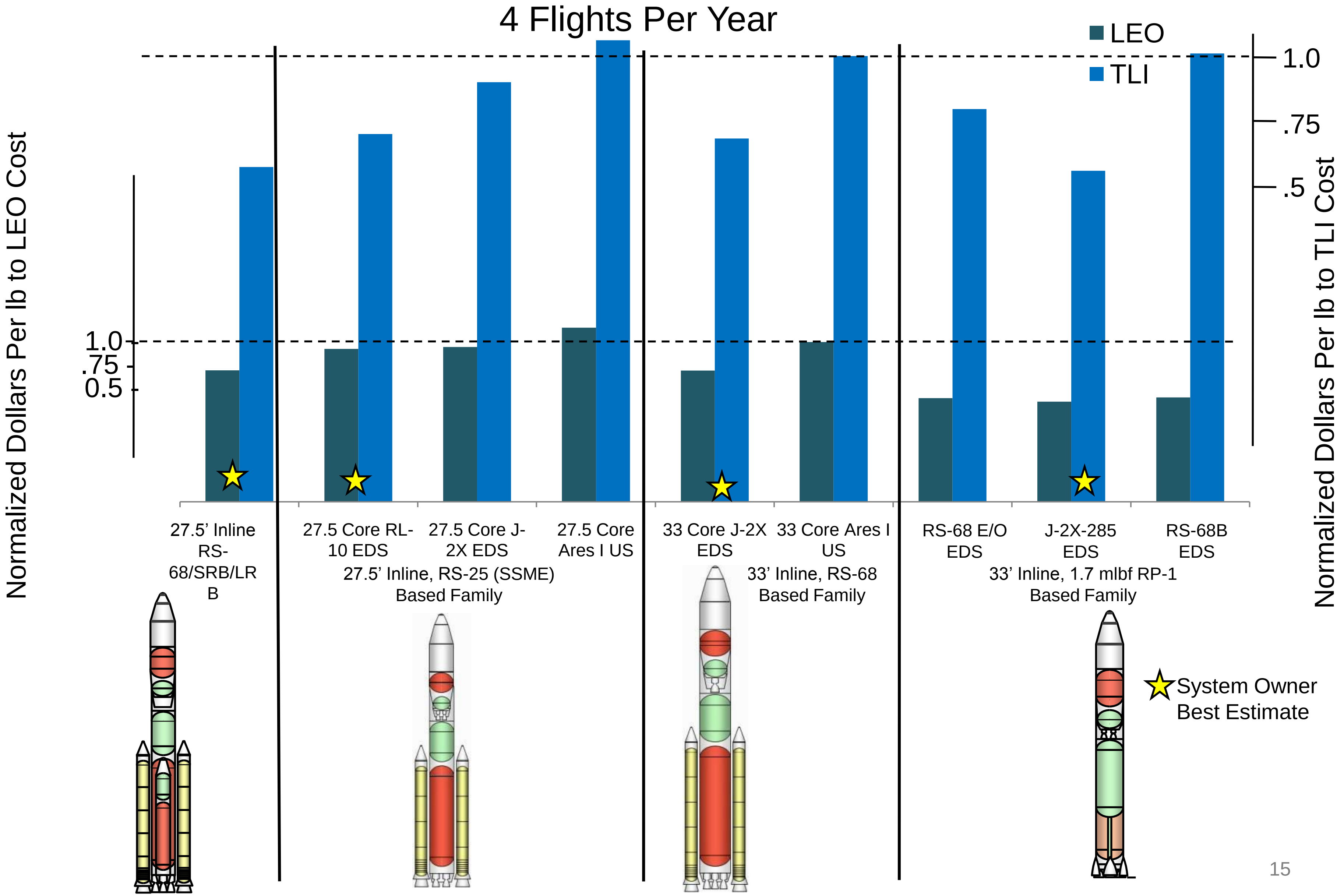
Dollars per Pound



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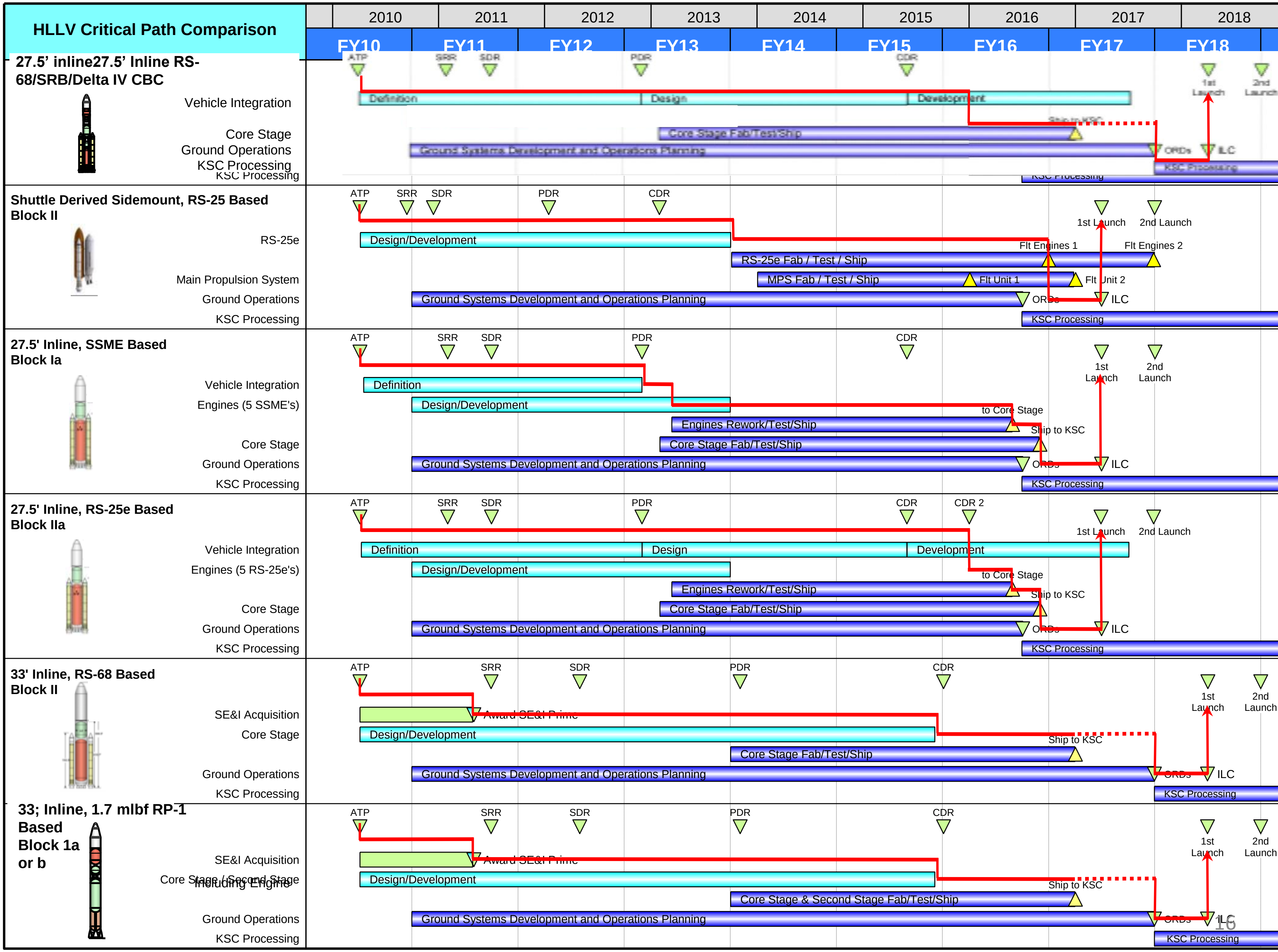
Schedule for Unconstrained Budget



Data Summary

- All In-line vehicle options studied can evolve to satisfy performance required for most missions assessed
  - Marginal Mission Capture for NEOs (2 launch scenario)
- Loss of Crew and Loss of Mission during launch discriminators :
  - Side-mount LOC lower due to lower abort effectiveness
  - 3.5 stage RP LOV lower due to number of engines
- The Core Stage and Ground Systems are the Critical Path for a Heavy Lift Capability
  - Sidemount and 27.5' RS-25 E in-line vehicles one year earlier than 33' and RP options
- Cost :
  - All options within 20% for total cost to initial human flight (Within Estimating Uncertainty)
  - Annual recurring cost at 4 flights per year within 10% for all options (Within Estimating Uncertainty)
- Note: Technologies being developed in the President's new plan will likely greatly reduce mass requirements for exploration missions, which will affect costs and tradeoffs among launch vehicles

Acronyms

Blk – Block
CEV – Crew Exploration Vehicle
CCB – Common Core Booster
Cx – Constellation Program
DDTE – Design, Development, Test, Evaluation
DRA – Design Reference Architecture
ET – External Tank
HLLV – Heavy Lift Launch Vehicle
HTPB – Hydroxyl Terminated Polybutadiene
HSF – Human Space Flight
IOC – Initial Operational Capacity
IHF – Initial Human Flight
ISS – International Space Station
IMLEO – Initial Mass Low Earth Orbit
L1 or L2 – Lagrange Point 1 or 2
LCC – Life Cycle Cost
LEO – Low Earth Orbit
LOX – Liquid Oxygen
LOC – Loss of Crew
LOM – Loss of Mission
LOV – Loss of Vehicle
LRB – Liquid Rocket Booster
NEO – Near Earth Object
PBAN – Polybutadiene Acrylonitrile
RP – Rocket Propellant
SSME – Space Shuttle Main Engine
SRB – Solid Rocket Booster
TLI – Trans Lunar Injection